Gas Scintillation Proportional Counters for High-Energy X-ray Astronomy

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ABSTRACT

A focal plane array of high-pressure gas scintillation proportional counters (GSPC) for a balloon-borne hard-x-ray telescope is under development at the Marshall Space Flight Center. These detectors each have an active area of ~ 20 cm^2, and are filled with a high pressure (10^6 Pa) xenon-helium mixture. Imaging is via crossed-grid position-sensitive phototubes sensitive in the UV region. The performance of the GSPC is well matched to that of the telescope's x-ray optics which have response to 75 keV and a focal spot size of ~ 500 µm. The detector's energy resolution, 4% FWHM at 60 keV, is adequate for resolving the broad spectral lines of astrophysical importance and for accurate continuum measurements. Full details of the instrument and its performance will be provided.

Keywords: x-ray astronomy instrumentation, x-ray detectors, proportional counters.

1. INTRODUCTION

Marshall Space Flight Center (MSFC) is constructing a new balloon-borne hard-x-ray payload. Termed HERO, for High Energy Replicated Optics, the payload features grazing incidence optics, which will give unprecedented sensitivity in an energy region from 15 keV (set by atmospheric attenuation) to 75 keV (cutoff energy for iridium coating of the mirror surface). The full payload, scheduled for flight in 2005 (although a partial payload will fly in 2004), consists of 16 mirror modules with half power diameters of 15 arc seconds coupled with a corresponding array of imaging detectors. The use of high-resolution x-ray mirrors places stringent requirements on the imaging detectors used in the focal plane. The detectors must have good response over the mirror's operational energy band, good spatial resolution to accurately resolve the mirror's focal spot, good background rejection for sensitive measures in a high background environment, and good energy resolution to resolve features in a sources spectrum. Finally they must be rigid enough for use in a space environment, light-weight, and consume little power.

We have selected Gas Scintillation Proportional Counters to meet these requirements. This type of detector currently offers the best combination of energy resolution, spatial resolution, and low background for the hard-x-ray region, in an area format more than adequate to cover the full HERO image plane. They have been well-developed for low energy use, flown on both the ASCA [1] and SAX [2] missions, and their extension to higher energies is a relatively straightforward matter of increasing the fill-gas pressure. Our detectors use high-purity xenon with 4 % helium to control the drift velocity at a total fill-gas pressure of 10^6 Pa.

We describe here the design of the HERO GSPC and present the results obtained from units flown on a proving flight in 2001 as well as a new design, modified to reduce size and weight, which will fly in 2004.

2. DETECTOR DESIGN AND OPERATION

2.1 HERO GSPC design

A schematic of the latest HERO gas scintillation proportional counter design is shown in Figure 1. At left is a collimation tube to prevent a detection of atmospheric gamma rays, followed by a low pressure beryllium window installed to seal off a main beryllium widow which operates at high voltage. The low pressure beryllium window is isolated from the main beryllium window by ceramic and the space between the windows is filled with 10^5 Pa of air. Fill

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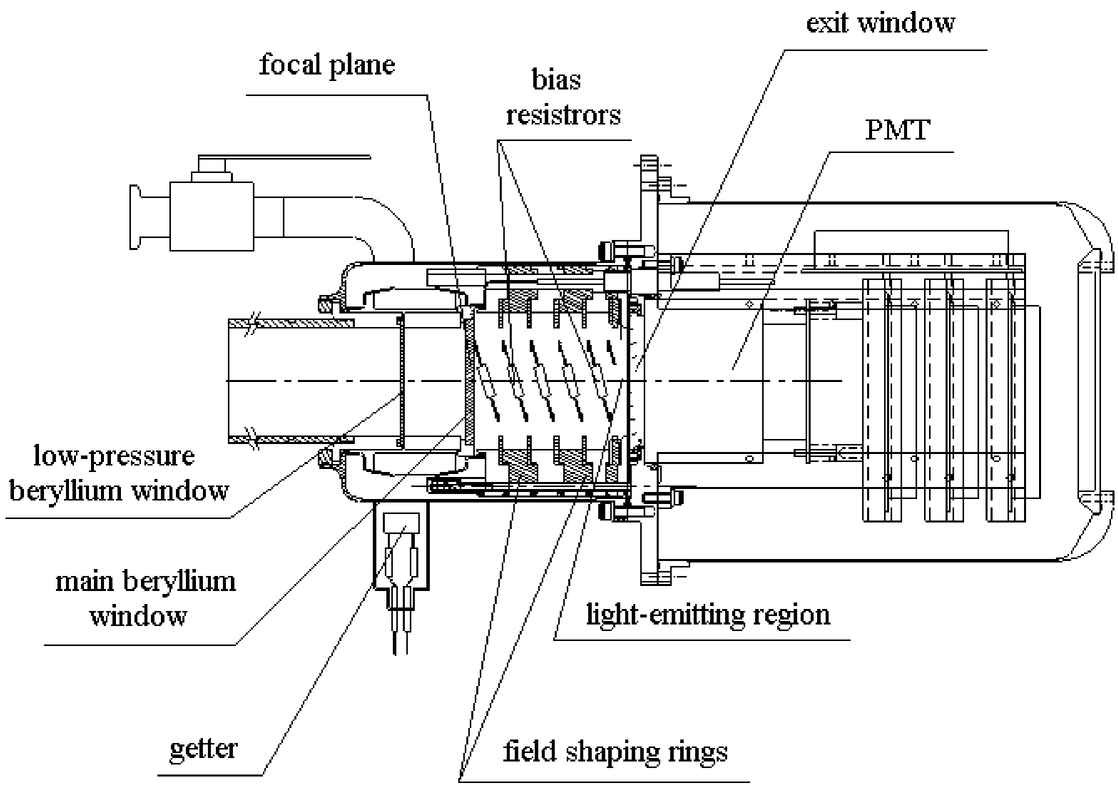

Figure 1. A schematic of the new GSPC flight detectors. Nickel grids which constrain the UV light emitting region are not shown.

gas is contained in a steel chamber with two main windows: one a 3.2 mm thick main beryllium window through which the x rays enter and the other, a 9 mm thick fused quartz window through which the resulting scintillation light exits. The fill gas is xenon with 4% helium at a pressure of 10^6 Pa. The absorption efficiency of the gas mixture used in our detector is shown in Figure 2. The depth of the absorption and drift region is 55 mm. A 4 mm light-emitting region is formed from a pair of nickel grids of geometrical transparency 98%. The lower grid is 4 mm above the UV transmitting exit window made from fused quartz, which is vacuum brazed into a stainless frame. Bias voltage is split such that a negative high voltage is applied to the entrance beryllium window, the upper grid is grounded and the lower grid is run at positive high voltage. A Hammatsu 4268 position sensitive photomultiplier tube (PMT) is attached to the exit window to register the (170 nm) xenon scintillation light.

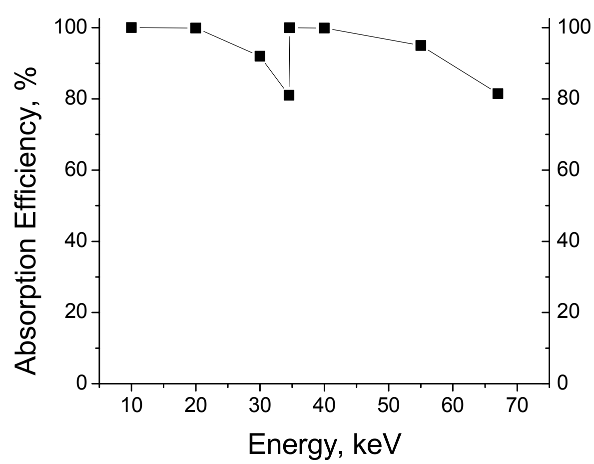

Figure 2. Calculated absorption efficiency of the HERO GSPC

The Hammatsu 4268 PMT utilizes a 32 (16 x 16) channel readout. In order to reduce the number of channels to be digitized, eight groups of four readout channels each are formed. Such clustering of signals allows significantly reduced bandwidth without significant loss in spatial resolution. The output signals from the PMT are each digitized by Analog-Digital Converters (ADC) over a 20 μsec interval at sample rate of 5 MHz. This timing interval is chosen based on the time necessary for fluorescent pairs to drift through the absorption region of the detector, and the chosen sample rate is adequate for background rejection based on rise time discrimination. This timing permits separation of the pair events formed when the gas de-excites by fluorescence photons which are then absorbed elsewhere in the detector sensitive volume. Without this separation, the weighted mean position for these two events would degrade the detector's spatial resolution. The data obtained from the ADC are stored in the flight data recorder. A portion of the data are sent to the ground, at a 600 kb rate, to monitor the health of the detectors during flight

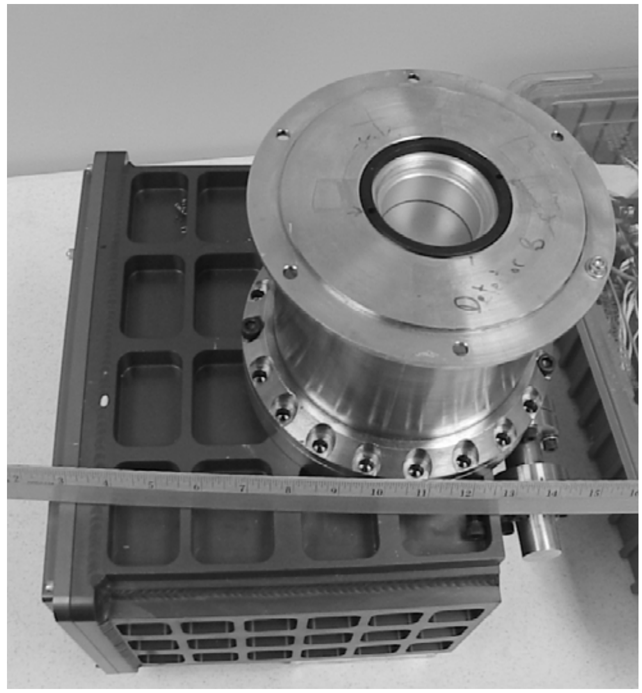

Figure 3. A Hero GSPC (proving) flight unit. The body of the detector sits on a square electronic box, which contains the PMT, the high voltage supplies and the front-end electronics. The collimator tube is removed to show the low-pressure beryllium entrance window.

As GSPC's are notoriously sensitive to contamination, a major challenge for high-pressure operation has been to maintain purity over extended periods. This is accomplished through an all-stainless-steel and ceramic construction, save for the entrance and exit windows, with only two (copper gasket) external seals, plus the addition of a small amount of helium to speed up the drift velocity and the incorporation of a Zr-V-Fe gas-purifying getter.

A prototype detector unit, which we assembled, tested and flew in 2001, is shown in Figure 3. We optimized the drift voltage, checked linearity of the detector and measured the spatial and energy resolution of the detector. These results are presented below. Our latest design which we are just constructing, shown schematically in figure 1, has identical interior layout, and hence identical performance, but has been modified externally to reduce weight and size.

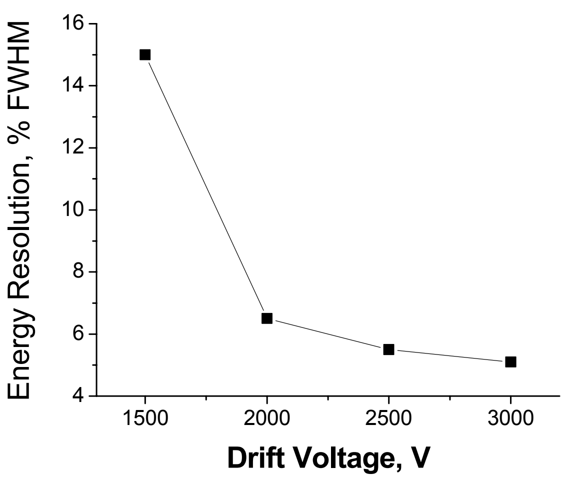

Figure 4. Energy resolution at 44 keV as a function of drift voltage

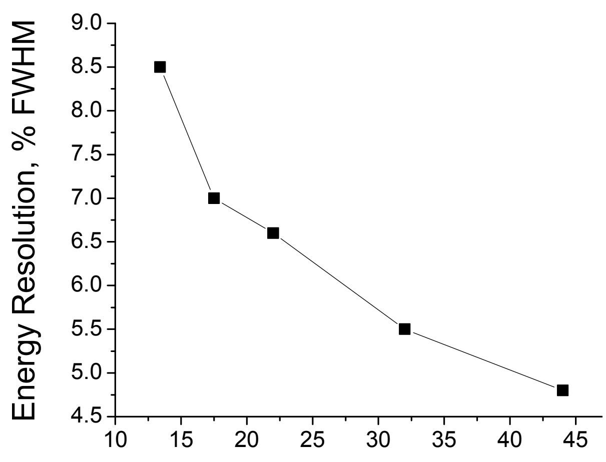

Figure 5. Energy resolution as a function of energy at 3000V drift

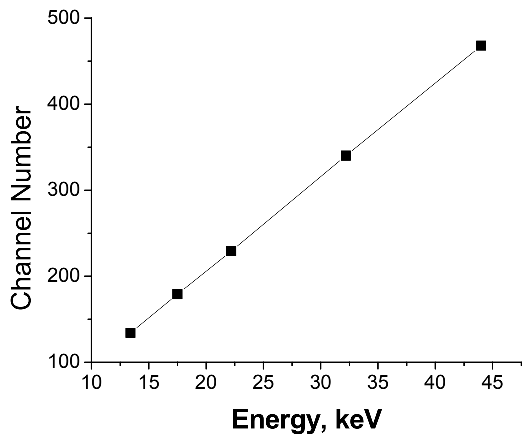

Figure 6. Linearity of the detector

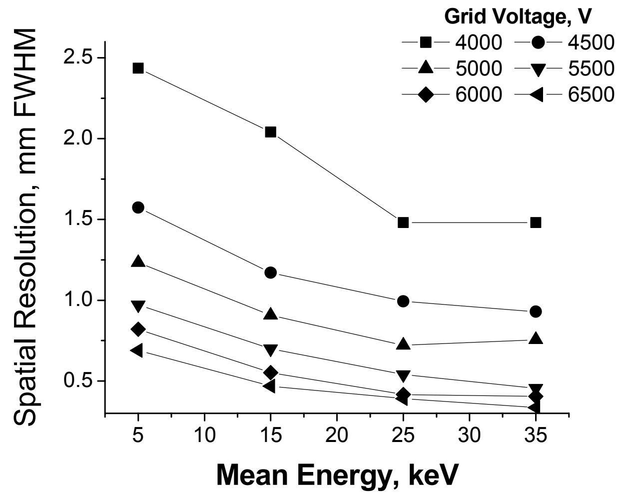

Figure 7. Spatial resolution of the detector as function of energy, measured with continuum x-ray source for various grid voltages.

Table 1: GSPC Parameters

Sensitive Area	Approximately 20 cm^2
Fill Gas	50 mm of Xenon + Helium (96/4) at 10^6 Pa
Entrance Window	3.2 mm Beryllium
Light Emitting Region	4 mm deep
Exit Window	9 mm of UV-transmitting glass
Phototube	Hamamatsu 4268, postion-sensitive, quartz window
Quantum Efficiency	99% at 40 keV, 89% at 60 keV
Measured Energy Resolution (FWHM)	5.5% at 32 keV, 5.1% at 60 keV
Measured Spatial Resolution (FWHM)	~ 400 µm, above 25 keV

2.2 Drift performance

In order to optimize the drift voltage of the GSPC we used a collimated x-ray beam (about 2 mm diameter) and an TbK_α source. The detector energy resolution for 44 keV was then measured as function of the drift voltage. The results of these measurements are shown in figure 4. The energy resolution was found to be 5.1+/- 0.3% (FWHM) at drift voltage of 3000 V, and to not improve above that, so that voltage was set for the remaining measurements.

2.3 Energy resolution and Linearity

The energy resolution of the HERO GSPC was measured using collimated beam of x-rays at variety of energies: 44.5 keV (Tb-K_α), 32.2 keV (Ba-K_α), 22.2 keV (Ag-K_α), 17.5 keV (Mo-K_α), 13.4 keV (Rb-K_α). The results of these measurements are shown in figure 5. Using the spectrum collected in these measurements we also checked the linearity of the detector. The channel number of multichannel analyzer, corresponding to the centroid of the characteristic line, is plotted as function of the x-ray energy. It can be seen in figure 6, the amplitude of the output signal of the detector is linear with x-ray energy.

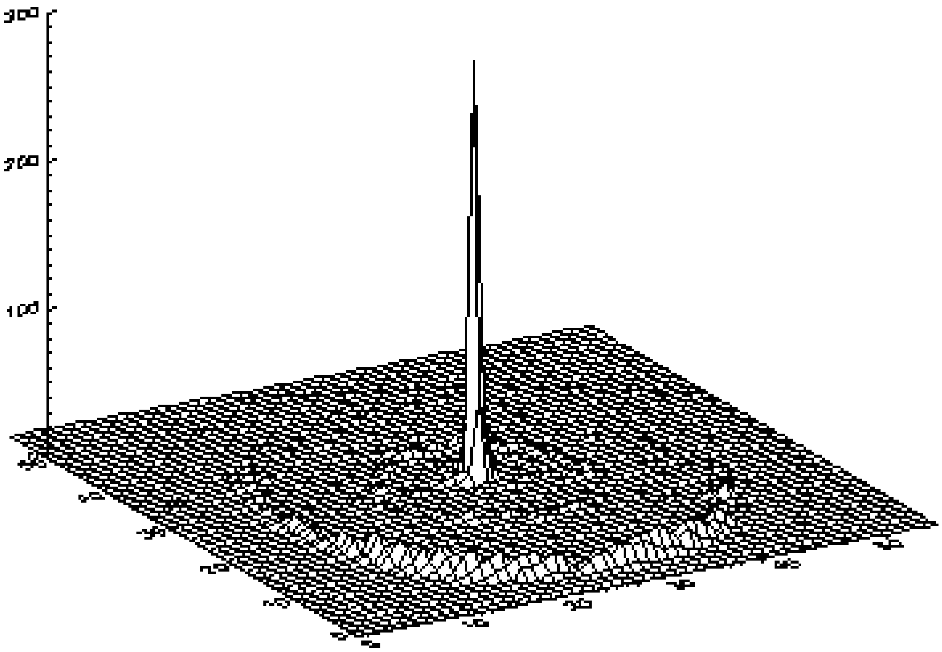

Figure 8. Image of focused x-rays taken by HERO GSPC.

2.4 Spatial resolution

The spatial resolution measurements were made by measuring the x-ray spot produced by collimated (100 µm diameter) beam from electron impact source run at a potential of 50 keV with a Cu target. The spatial resolution of the HERO GSPC was measured for different grid voltages. Because of breakdown in the detector the maximum grid voltage is limited to 6500 V. The results of these measurements are shown in figure 7.

2.5 Detector performance summary

The parameters of our GSPC design are summarized in Table 1. The performance listed meets our expectations; The energy resolution, 5.5 % at 32 keV, is slightly poorer than that obtained with lower pressure devices, but this was anticipated as the thicker exit window, necessary to withstand the high fill-gas pressure, attenuates more of the ~ 170nm xenon scintillation light and also gives a slightly less favorable solid angle for light collection. The measured spatial resolution, 400 µm above 25keV, is close to that expected for the physical processes in the gas, but still limited by the light collection. It is adequate to resolve the focal spot of the anticipated 15 arc second optics (450 µm). Parallax effects, due to finite x-ray penetration depths is expected to be insignificant due to the extremely small cone angles of hard-x-ray optics. A background level of about 10^{-3} counts / cm^2 sec keV, measured during flight with no anticoincidence shield, is typical of gas-filled detectors. We expect that this would drop by a factor of two if an active shield were used.

The detector also benefits from the hygienic design which was described above. After initial bakeout at 100˚ C for 1 week, the current test units have operated for 2 years without any discernible degradation.

We also performed a test of the HERO GSPC in combination with a nickel replicated optic. The test was executed at MSFC's 100 meter long stray light facility. The continuum x-rays (up to 50 keV) were focused by 5.0-cm-diameter 6 meter focal length mirror with a half-power diameter of 25 arcsec. The image of focused x-rays taken by the HERO GSPC is shown in figure 8. The central spike is the focused image. Two rings can be seen in the picture. The inner ring represents the x-rays reflected only once from either the first or second segments of the optic. The outer ring corresponds to unblocked straight-through radiation .

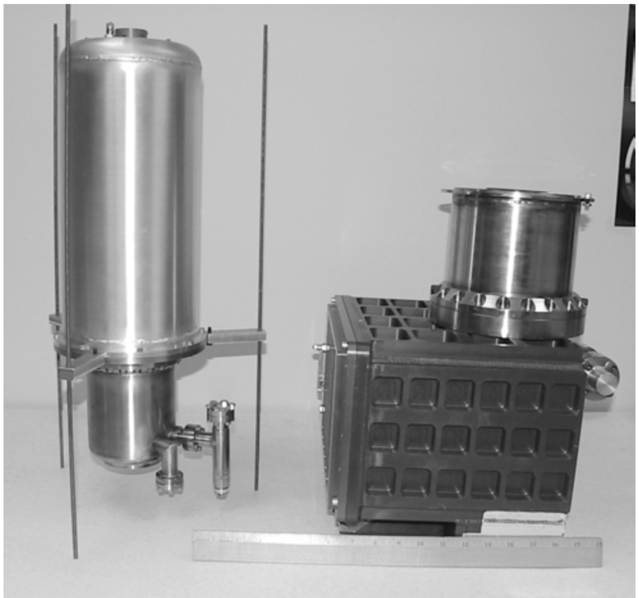
Figure 9. Latest design detector (on left) and prototype detector (on right).

2.6 New design detector

Although the performance of the prototype GSPC described above was adequate for the proving flight, where only two mirror modules were flown, it is quite bulky and unsuited for the future more densely-packed focal plane of the payload.

We have re-designed the pressure chamber and electronics housing to greatly reduce the detectors footprint and mass and are just assembling these units for testing. The photograph of redesigned detector standing next to the prototype detector is shown in figure 9. The new design features the same internal dimensions as for prototype design so we expect to have the same level of performance, but the footprint and mass of the detector have been significantly reduced. The new detector weighs 8.1 kg compared to 25.9 kg for the prototype detector. The new detector footprint is 19 cm diameter (the mating flange), although the body is only 11.2 cm diameter. The old footprint was 33.0 cm x 35.6 cm.

The first flight of the new HERO payload, with 8 re-designed detectors, is set for May 2004. A second flight, scheduled for 2005, will have 16 such detectors inside the HERO 1-m-diameter optical bench, a packing density that would not have been possible with the old GSPC design..

3. CONCLUSIONS

The HERO prototype gas scintillation proportional counter, which we assembled, tested and flew, has demonstrated adequate efficiency (89% at 60 keV), and energy (5.1% at 60 keV) and position (~ 400 µm, above 35 keV) resolution to be used as an imaging detector for hard x-ray telescope. The stability, ruggedness and reliability of this type of the detector make it ideal for balloon borne astronomical observations. However, the prototype detector is rather massive and bulky, and 16 detectors, planned for the future payload, would not fit the HERO optical bench space.

We have redesigned the detector unit to significantly reduce weight and size. The redesigned detector has identical interior layout, and is expected to have identical performance. It weights only 8.1 kg and its 19 cm diameter footprint makes it possible to place all required detectors inside of 1-meter tube of the HERO platform. Currently an array of eight GSPC detectors is under development at Marshall Space Flight Center. The performance of the array will be reported in the near future.

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